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B Factory Constraints on Isosinglet Down Quark Mixing, and Predictions For Other CP Violating Experiments

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Abstract

In the main part of the paper we project forward to having B factory determinations of $\sin(2\beta)$ and $\sin(2\alpha)$, for which we take several values. First, we use a joint χ^2 analysis of CKM experiments to constrain CKM matrix elements in the standard model, and experiments on the angles α, β, and γ, and on x_s and null CP asymmetries. Then we invoke mixing to a new isosinglet down quark (as in E_6) which induces FCNC that allow a Z^0 mediated contribution to $B - \bar{B}$ mixing and which brings in new phases. We then repeat the χ^2 analysis, now including experimental constraints from FCNC as well, finding much larger ranges of prediction for the B factory. We then add projected B factory results on $\sin(2\beta)$ and $\sin(2\alpha)$ and repeat both analyses. In (ρ, η) and $(x_s, \sin(\gamma))$ plots for the extra isosinglet down quark model, we find multiple regions that will require experiments on $\sin(\gamma)$ and/or x_s to decide between and possibly to effectively bound out the extra down quark

contribution.

14.40.Nd, 11.30.Er, 11.30.Ly, 12.15.Mm

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I. INTRODUCTION

In this paper we are interested in finding the "reach" of the B factories in terms of determining the angles of the standard model (SM) CKM matrix, and of limiting "new physics" contributions. Within these future limits on both models, we then make predictions for other experiments, including $\sin(\gamma)$, x_s, and the asymmetry in $B_s - \bar{B}_s$ mixing, which is almost null in the SM. In setting limits we use the method of a joint χ^2 fit to all constraining experiments. The "new physics" class of models we use are those with extra iso-singlet down quarks, where we take only one new down quark as mixing significantly. An example is E_6, where there are two down quarks for each generation with only one up quark, and of which we assume only one new iso-singlet down quark mixes strongly. This model has shown large possible effects in $B - \bar{B}$ mixing phases. The "reach" of the B factory in this model also sets limits on the phases of the mixing angles to the new iso-singlet down quark. For different $\sin(2\alpha)$ we find multiple regions that will require experiments on $\sin(\gamma)$ or x_s to decide between, and experiments on both could be required to effectively bound out or to verify the model. We also find a relatively small $B_s - \bar{B}_s$ mixing asymmetry, even outside the standard model.

II. ISO-SINGLET DOWN QUARK MIXING MODEL

Groups such as E_6 with extra $SU(2)_L$ singlet down quarks give rise to flavor changing neutral currents (FCNC) through the mixing of four or more down quarks [1–4]. We use the 4×4 down quark mixing matrix V which diagonalizes the initial down quarks (d^0_{iL}) to the mass eigenstates (d_{jL}) by $d^0_{iL} = V_{ij} d_{jL}$. The flavor changing neutral currents we have are [3,4] $-U_{ds} = V^*_{4d} V_{4s}$, $-U_{sb} = V^*_{4s} V_{4b}$, and $-U_{bd} = V^*_{4b} V_{4d}$. These FCNC with tree level Z^0 mediated exchange may contribute part of $B^0_d - \bar{B}^0_d$ mixing and of $B^0_s - \bar{B}^0_s$ mixing, giving a range of non-zero values for the fourth quark's mixing parameters. $B^0_d - \bar{B}^0_d$ mixing may occur by the $b - \bar{d}$ quarks in a $\bar{B}_d$ annihilating to a virtual Z through a FCNC with

amplitude U_{db} , and the virtual Z then creating $\bar{b}-d$ quarks through another FCNC, again with amplitude U_{db}, which then becomes a B_d meson. If these are a large contributor to the $B_d - \bar{B}_d$ mixing, they introduce three new mixing angles and two new phases into the CP violating B decay asymmetries. The size of the contribution of the FCNC amplitude U_{db} as one side of the unitarity quadrangle is less than 0.1 of the unit base $|V_{cd}V_{cb}|$ at the 1-σ level, but we have found [1,3,4] that it can contribute, at present, as large an amount to $B_d - \bar{B}_d$ mixing as does the standard model. The new phases can appear in this mixing and give total phases different from that of the standard model in CP violating B decay asymmetries [3–7].

For $B_d - \bar{B}_d$ mixing with the four down quark induced $b-d$ coupling, U_{db}, we have [5]

$$x_d = (2G_F/3\sqrt{2})B_B f_B^2 m_B \eta_B \tau_B \left|U_{std-db}^2 + U_{db}^2\right| \tag{2.1}$$

where with $y_t = m_t^2/m_W^2$

$$U_{std-db}^2 \equiv (\alpha/(4\pi \sin^2\theta_W))y_t f_2(y_t)(V_{td}^* V_{tb})^2, \tag{2.2}$$

and $x_d = \Delta m_{B_d}/\Gamma_{B_d} = \tau_{B_d}\Delta m_{B_d}$.

The CP violating decay asymmetries depend on the combined phases of the $B_d^0 - \bar{B}_d^0$ mixing and the b quark decay amplitudes into final states of definite CP. Since we have found that Z mediated FCNC processes may contribute significantly to $B_d^0 - \bar{B}_d^0$ mixing, the phases of U_{db} would be important. Calling the singlet down quark D, to leading order the mixing matrix elements to D are $V_{tD} \approx s_{34}$, $V_{cD} \approx s_{24}e^{-i\delta_{24}}$, and $V_{uD} \approx s_{14}e^{-i\delta_{14}}$. The FCNC amplitude U_{db} to leading order in the new angles is

$$U_{db} = -s_{34}(s_{34}V_{td}^* + s_{14}e^{-i\delta_{14}} - s_{24}e^{-i\delta_{24}}s_{12}). \tag{2.3}$$

where $V_{td} \approx (s_{12}s_{23} - s_{13}e^{i\delta_{13}})$, and $V_{ub} = s_{13}e^{-i\delta_{13}}$.

III. JOINT CHI-SQUARED ANALYSIS FOR CKM AND FCNC EXPERIMENTS

FCNC experiments put limits on the new mixing angles and constrain the possibility of new physics contributing to the $B_d^0 - \bar{B}_d^0$ and $B_s^0 - \bar{B}_s^0$ mixing. Here we analyze jointly all

constraints on the 4×4 mixing matrix obtained by assuming only one of the $SU(2)_L$ singlet down quarks mixes appreciably [3]. We use the eight experiments for the 3×3 CKM submatrix elements [8], which include those on the five matrix elements $V_{ud}, V_{cd}, V_{us}, V_{ub}, V_{cb}$ of the u and c quark rows, and, in the neutral K system [9], include $|\epsilon|$ and $K_L \to \mu\mu$, and also $B_d - \bar{B}_d$ mixing. For studying FCNC, we add [5] the $B \to \mu\mu X$ bound (which constrains $b \to d$ and $b \to s$), $K^+ \to \pi^+ \nu\bar{\nu}$ [7,10,11] and $Z^0 \to b\bar{b}$ [7] (which directly constrains the V_{4b} mixing element). FCNC experiments will bound the three amplitudes U_{ds}, U_{sb}, and U_{bd} which contain three new mixing angles and three phases. We use the newly indicated mass of the top quark as $m_t = 174$ GeV.

In maximum likelihood correlation plots, we use for axes two output quantities which are dependent on the angles, such as ρ and η, and for each possible bin with given values for these, we search through the nine dimensional angular data set of the 4×4 down quark mixing angles, finding all sets which give results in the bin, and then putting into that bin the minimum χ^2 among them. To present the results, we then draw contours at several χ^2 in this plane corresponding to given confidence levels.

IV. CONSTRAINTS ON THE STANDARD MODEL CKM MATRIX AT PRESENT, AND AFTER THE B FACTORY

We first analyze the standard model using the present constraints on the eight CKM related experiments, and then repeat the analysis using the projected constraints from the B factory [12] which will give values for $\sin(2\beta)$ and $\sin(2\alpha)$. In the following, we will find and take $\sin(2\beta) = 0.62$ as the center of the current range with its projected B factory errors of ± 0.06 [13], and vary $\sin(2\alpha)$ from -1.0 to 1.0, using the projected B factory errors of ± 0.08.

In Fig. 1 is shown the (ρ, η) plot for the standard model with contours at χ^2 which correspond to confidence levels (CL) that are the same as the CL for 1, 2, and 3-σ limits. Fig. 1 shows large regions for the present CKM constraints, and small regions for the projected B

factory results, where we have taken the cases $\sin(2\alpha) = 1, 0$, and -1, which appear from left to right, respectively.

In Fig. 2 is shown the $(\sin(2\alpha), \sin(2\beta))$ plot for the standard model, for the same cases as in Fig. 1. The nearly horizontal contours are the present constraints, and the small circular contours are those for the B factory cases $\sin(2\alpha) = -1, 0$, and 1, centered about their appropriate $\sin(2\alpha)$ values.

In Fig. 3 is shown the $(x_s, \sin(\gamma))$ plot for the standard model with (a) present data, and (b) for the B factory cases $\sin(2\alpha) = 1, 0, -1$ from left to right. x_s is determined here from $x_s = 1.2 x_d (|V_{ts}|/|V_{td}|)^2$. The largest errors arise from the uncertainty in $|V_{td}|$, since we have not assumed any improvement in the present 20% uncertainty in $\sqrt{B_B} f_B$ (which relates V_{td} to x_d) from lattice calculations [14]. The B factory in the SM constructs a rigid triangle from the knowledge of α and β, and removes this uncertainty in γ and x_s in the future. A cautionary note for experiments emerges from this plot, namely that $\sin(\gamma)$ is close to one (0.8 to 1.0) for the 1-σ contour, and high accuracy on $\sin(\gamma)$ will be needed to add new information to the standard model. At 1-σ the range of x_s in the standard model is from 11 to 24. It is clear that the choices of $\sin(2\alpha)$ cases gives distinct ranges for x_s. Using x_s to agree with the range given by a $\sin(2\alpha)$ measurement will be a good test of the standard model.

V. CONSTRAINTS ON THE FOUR DOWN QUARK MODEL AT PRESENT, AND AFTER THE *B* FACTORY RESULTS

Here we also project forward to having results on $\sin(2\alpha)$ and $\sin(2\beta)$ from the B factories, and show how there will be stronger limits on the new phases of FCNC couplings than from present data. In the four down quark model we use "$\sin(2\alpha)$" and "$\sin(2\beta)$" to denote results of the appropriate B_d decay CP violating asymmetries, but since the mixing amplitude is a superposition, the experimental results are not directly related to angles in a triangle in this model. The asymmetries with FCNC contributions included are

$$\sin(2\beta) \equiv A_{B_d^0 \to \Psi K_s^0} = \mathrm{Im}\left[\frac{(U_{std-db}^2 + U_{db}^2)}{|U_{std-db}^2 + U_{db}^2|}\frac{(V_{cb}^* V_{cs})}{(V_{cb}^* V_{cs})^*}\right] \tag{5.1}$$

$$\sin(2\alpha) \equiv -A_{B_d^0 \to \pi^+\pi^-} = -\mathrm{Im}\left[\frac{(U_{std-db}^2 + U_{db}^2)}{|U_{std-db}^2 + U_{db}^2|}\frac{(V_{ub}^* V_{ud})}{(V_{ub}^* V_{ud})^*}\right] \tag{5.2}$$

with U_{std-db} defined in Eqn. (2.2).

We analyze all of these constraints together using a joint χ^2 for fitting all of the thirteen experiments in the nine parameter angle space of the 4×4 mixing matrix. We include both the standard model and FCNC contributions through effective Hamiltonians [5]. We then make maximum likelihood plots which include ($\sin(2\alpha)$, $\sin(2\beta)$), (ρ, η), (x_s, $\sin\gamma$), and those involving the FCNC amplitudes U_{db} and U_{sb} (not shown).

The corresponding plots for the four down quark model are shown for present data and for projected B factory data in the following figures. In the figures, we show χ^2 contour plots with confidence levels (CL) at values equivalent to 1-σ and at 90% CL (1.64σ) for present data, and for projected B factory results. Again, for results with the B factories, we use the example of the most likely $\sin(2\beta) = 0.62$ with B factory errors of ± 0.06, and errors of ± 0.08 on $\sin(2\alpha)$.

In Fig. 4 we have plotted the χ^2 contours for the location of the vertex of $V_{ub}^* V_{ud}/|V_{cb} V_{cs}| \equiv \rho + i\eta$ (even for the four down quark quadrangle case). We note that in contrast to the standard model, in Fig. 4a the presently allowed contours in the four down quark model go down to $\eta = 0$ at the 90% CL, which can result from the FCNC with its phases in U_{db} causing the known CP violation. In Fig. 4b,c and d we show the B factory cases of $\sin(2\alpha) = -1, 0$ and 1, respectively, with contours at 1-σ and at 90% CL. The existence of several regions requires that extra experiments in $\sin(\gamma)$ or x_s will also be needed to verify or to bound out the extra down quark mixing model. The larger contours at 1-σ roughly agree with those of the standard model in Fig. 1. In our χ^2 we have used [8,5] $|V_{ub}| = 0.071 \pm 0.013$ consistent with adjusting κ in the Isgur-Wise model to fit the spectra, and using the spread of model results to determine a σ. In any case, we can consider this accuracy as obtainable in the future, following ref. [12]. Use of the conservative bound of 0.08 ± 0.03 used by others still

results in multiple regions.

The $(\sin(2\alpha), \sin(2\beta))$ χ^2 contour plot for the four down quark model (not shown) shows that all values of $\sin(2\beta)$ and $\sin(2\alpha)$ are individually allowed at 1-σ, and most pairs of values are allowed at 1-σ. This is a much broader allowed region in $\sin(2\beta)$ than the standard model result from present data in Fig. 2. The allowed 1,2 and 3-σ contours in the ($\sin(2\alpha)$, $\sin(2\beta)$) plot for the cases of the B factory results with the four down quark model are very similar to the SM results shown in Fig. 2.

In terms of other experiments, the $(x_s, \sin(\gamma))$ plot for the four down quark model is shown in Fig. 5a with the allowed region from present data, with 1-σ and 90% CL contours. This allows all values of $\sin(\gamma)$ at the 1-σ CL at present, and at 1-σ constrains x_s to lie between 8 and 25. In the four down quark model, what we mean by "$\sin(\gamma)$" is the result of the experiments which would give this variable in the SM [15]. Here, the four down quark model involves more complicated amplitudes, and is not simply $\sin(\delta_{13})$

$$\sin(\gamma) = \mathrm{Im}\left[\frac{(U^2_{std-bs} + U^2_{bs})}{|U^2_{std-bs} + U^2_{bs}|}\frac{(V^*_{ub}V_{cs})}{|V_{ub}V_{cs})|}\right], \tag{5.3}$$

$$x_s = 1.2 x_d \frac{|U^2_{std-bs} + U^2_{bs}|}{|U^2_{std-db} + U^2_{db}|}, \tag{5.4}$$

where

$$U^2_{std-bs} = (\alpha/(4\pi \sin\theta_W{}^2))y_t f_2(y_t)(V^*_{tb}V_{ts})^2. \tag{5.5}$$

In Figs. 5b, c and d are shown the cases $\sin(2\alpha) = -1, 0$, and 1, respectively, at 1-σ and at 90% CL. They reflect the same regions that appeared in the (ρ, η) plots, Figs. 4b, c, and d. The resemblance is increased if we recall that roughly $\sin(\gamma) \approx \eta$, and also that $x_s \propto 1/|V_{td}|^2$ where $|V_{td}|$ is the distance from the $\rho = 1, \eta = 0$ point. We see that experiments on $\sin(\gamma)$ and x_s are necessary to resolve the possible regions allowed by the four down quark model. For the case of $\sin(2\alpha) = -1$, the allowed values of $\sin(\gamma)$ in Fig. 5b are smaller than those for the standard model in Fig. 3a.

The asymmetry A_{B_s} in B_s mixing in the standard model with the leading decay process of $b \to c\bar{c}s$ has no significant phase from the decay or from the mixing which is proportional

to V_{ts}^2. The vanishing of this asymmetry is a test of the standard model [2], and a non-zero value can result from a "new physics" model. With the FCNC, the new result is

$$A_{B_s} = \mathrm{Im}\left[\frac{(U_{std-bs}^2 + U_{bs}^2)}{|U_{std-bs}^2 + U_{bs}^2|}\frac{(V_{cb}^* V_{cs})}{(V_{cb}^* V_{cs})^*}\right] \tag{5.6}$$

The extent of the non-zero value of A_{B_s} in the four down quark model is shown in Fig. 6 from present data with contours at 1, 2 and 3-σ. Plots for the B factory cases (not shown) are similar. We note that it is bounded to be rather small from present data at 1-σ, i.e. less than 0.06, and less than 0.32 at 2-σ.

We compared the limits on the four down quark FCNC amplitude $|U_{db}|$ versus the standard model amplitude $|U_{std-db}|$ for $B_d^0 - \bar{B}_d^0$ mixing , at present and after the B factory results. At present the constraints are such that $|U_{db}|$ can go from zero up to as large as the magnitude of $|U_{std-db}|$ at 2-σ [5]. For the sample B factory results, the $|U_{db}|$ range is only somewhat more restricted. The total phase of $B_d^0 - \bar{B}_d^0$ mixing is closely restricted, however, to the same range as the standard model amplitude.

The 90% CL limits on the three new quark mixing elements $|V_{4d}|$, $|V_{4s}|$, and $|V_{4b}|$ are roughly equal to the mixing angles to the fourth down quark θ_{14}, θ_{24} and θ_{34}, respectively. They are bounded by 0.06, 0.05, and 0.14, respectively.

VI. CONCLUSIONS

The main conclusion with the four down quark model for the B factory cases is that there are multifold allowed regions as shown in the (ρ, η) plot and the $(x_s, \sin(\gamma))$ plot. This will require additional experiments on x_s and $\sin(\gamma)$ to well define the four down quark model results, and eventually to verify or bound out the relevance of the model here.

We note that in the four down quark model the $\eta \propto \mathrm{Im}(V_{ub}^*)$ range can reach zero, which is quite different than in the standard model. This is because the other phases can account for CP violation.

We have also found that the present range of x_s at 1-σ is from 11 to 24 in the standard

model, and from 8 to 25 in the four down quark model at 1-σ. The $\sin(\gamma)$ range is from 0.8 to 1.0 in the SM at 1-σ, and completely undetermined in the four down quark model at 1-σ.

Finally, the range of the B_s asymmetry which almost vanishes in the standard model, is found to range from zero up to 0.06 at 1-σ in the four down quark model. Although its presence is a signal against the standard model, it may be small in new physics models, as it is in this one, and thus hard to detect.

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FIGURES

FIG. 1. The (ρ, η) plot for the standard model, showing the 1, 2, and 3-σ contours, for the present data (large contours) and for projected B factory results (smaller circular contours) at $\sin(2\alpha) = 1, 0$, and -1 from left to right.

FIG. 2. The ($\sin(2\alpha)$, $\sin(2\beta)$) plot for the standard model at 1, 2, and 3-σ with present data (nearly horizontal contours), and with the sample results of the B factories (almost circular contours), for $\sin(2\alpha) = 1, 0$, and -1 from left to right.

FIG. 3. The (x_s, $\sin\gamma$) plots are shown for the standard model with: (a) present limits; and (b) sample results for the B factories for $\sin(2\alpha) = 1, 0$, and -1 from left to right.

FIG. 4. The (ρ, η) plots for the four down quark model from: (a) present data, and for B factory cases for values of $\sin(2\alpha)$ as labeled. Contours are at 1-σ and at 90% CL.

FIG. 5. The $(x_s, \sin(\gamma))$ plots for the four down quark model from (a) present data, and (b, c, and d) for B factory cases for values of $\sin(2\alpha)$ as labeled. Contours are the same as in Fig. 4.

FIG. 6. The (x_s, A_{B_s}) plot for the B_s asymmetry A_{B_s} in the four down quark model for present data, with contours at 1, 2 and 3-σ.

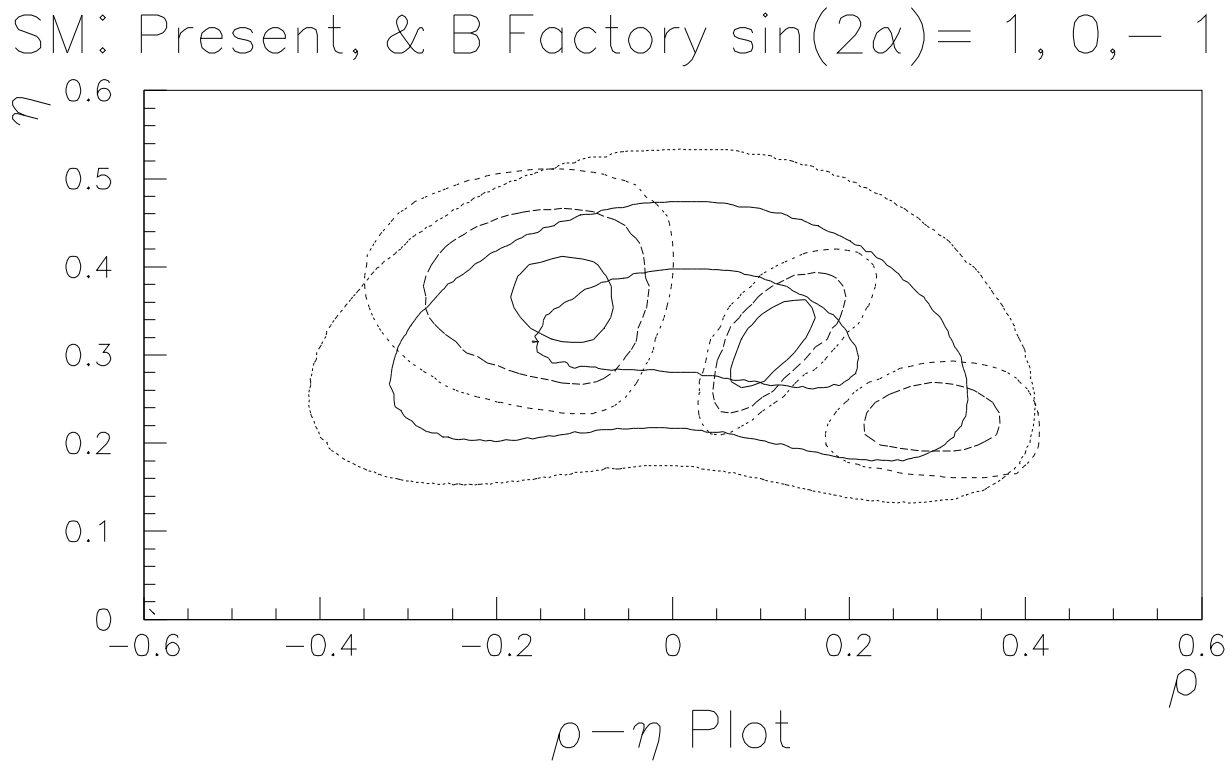

SM: Present, & B Factory sin(2α)= 1, 0,− 1
η
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
ρ
ρ−η Plot

Fig. 1

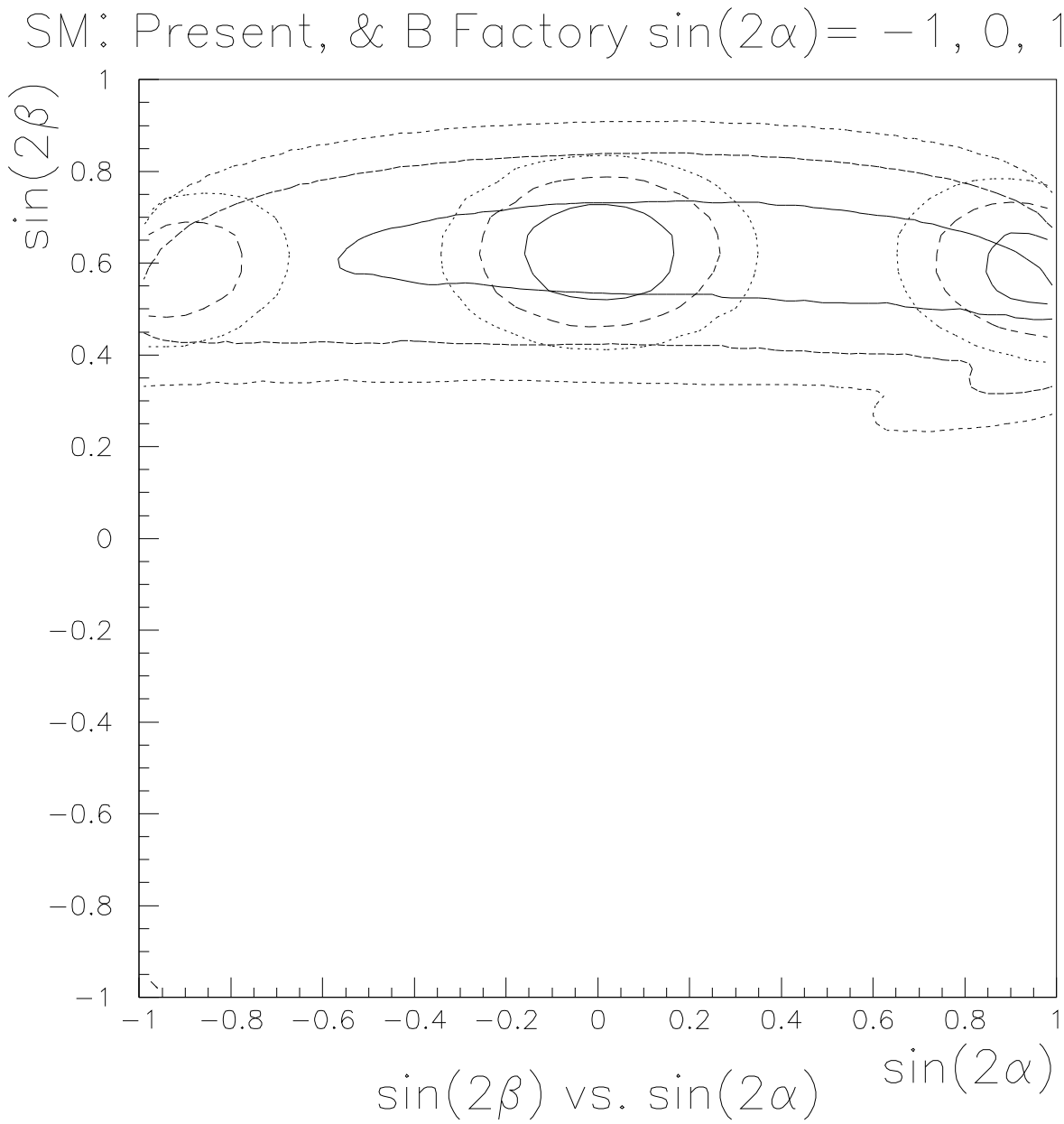
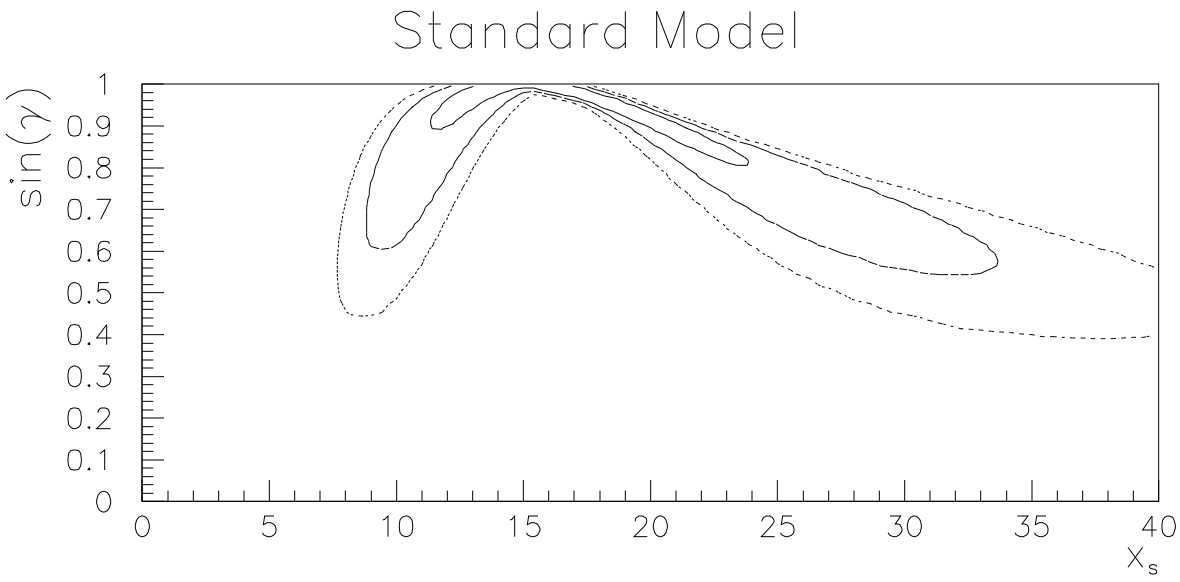
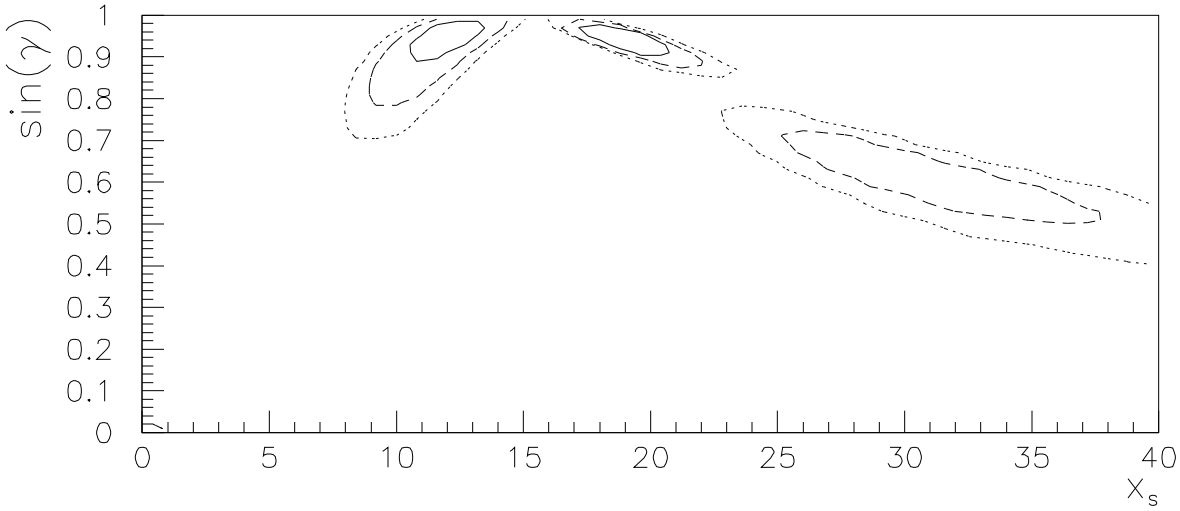

SM: Present, & B Factory sin(2α)= −1, 0, 1
sin(2β)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
sin(2α)
sin(2β) vs. sin(2α)

Fig. 2



(a) Present Data



(b) B Factory $\sin(2\alpha) = 1, 0, -1$

Fig. 3

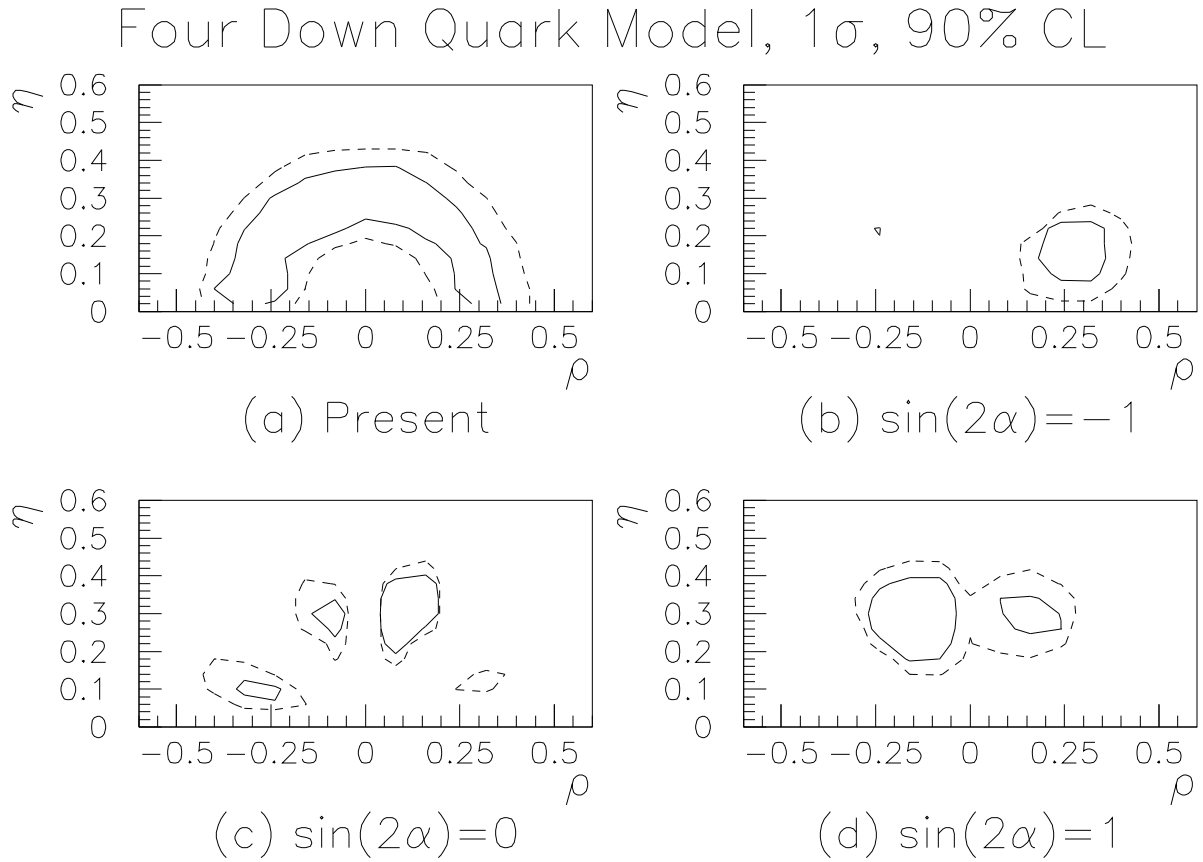

Four Down Quark Model, 1σ, 90% CL
η
ρ
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.5
−0.25
0
0.25
0.5
(a) Present
(b) sin(2α)=−1
(c) sin(2α)=0
(d) sin(2α)=1

Fig. 4

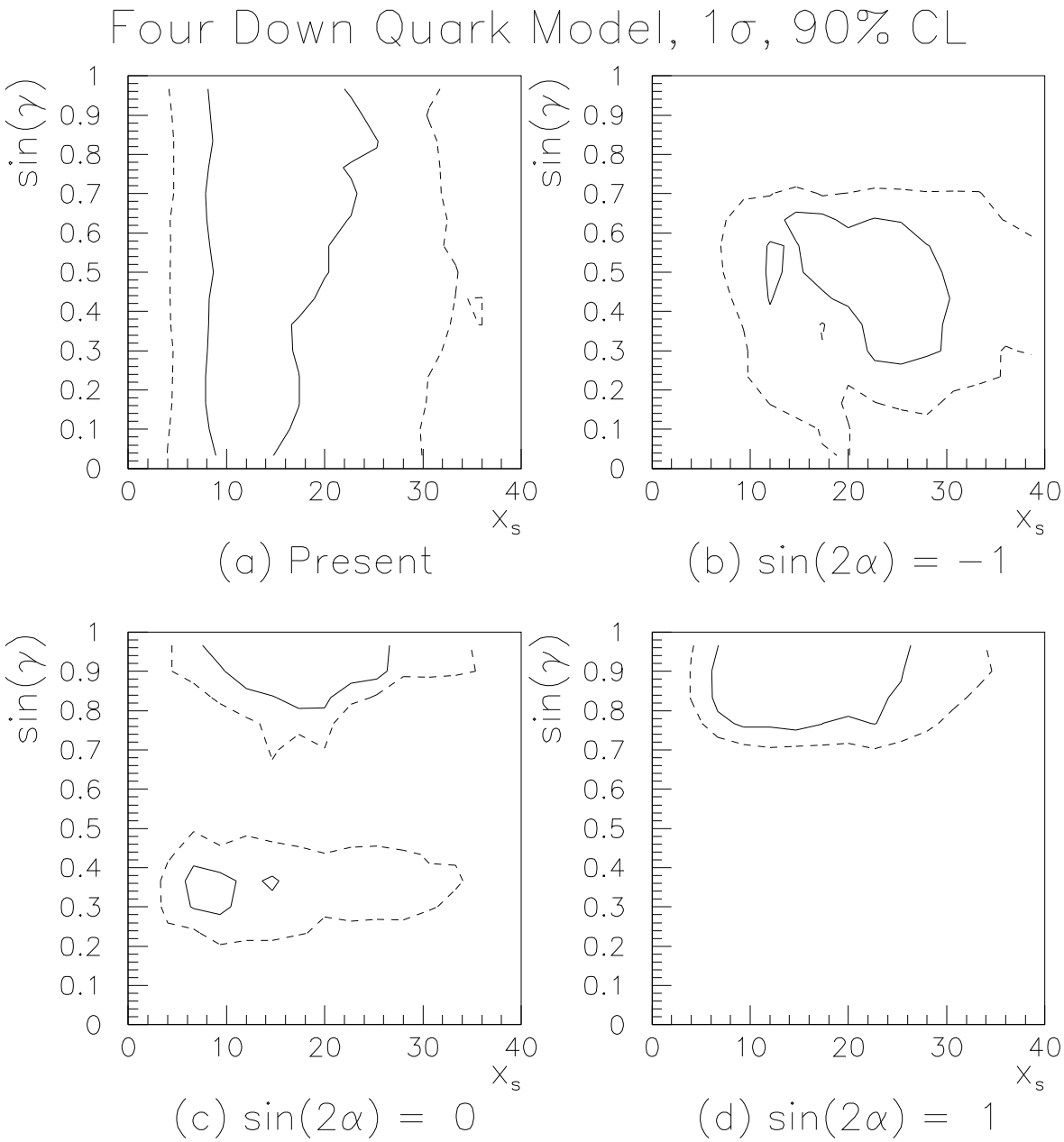

Four Down Quark Model, 1σ, 90% CL
sin(γ)
X_s
(a) Present
(b) sin(2α) = −1
(c) sin(2α) = 0
(d) sin(2α) = 1

Fig. 5

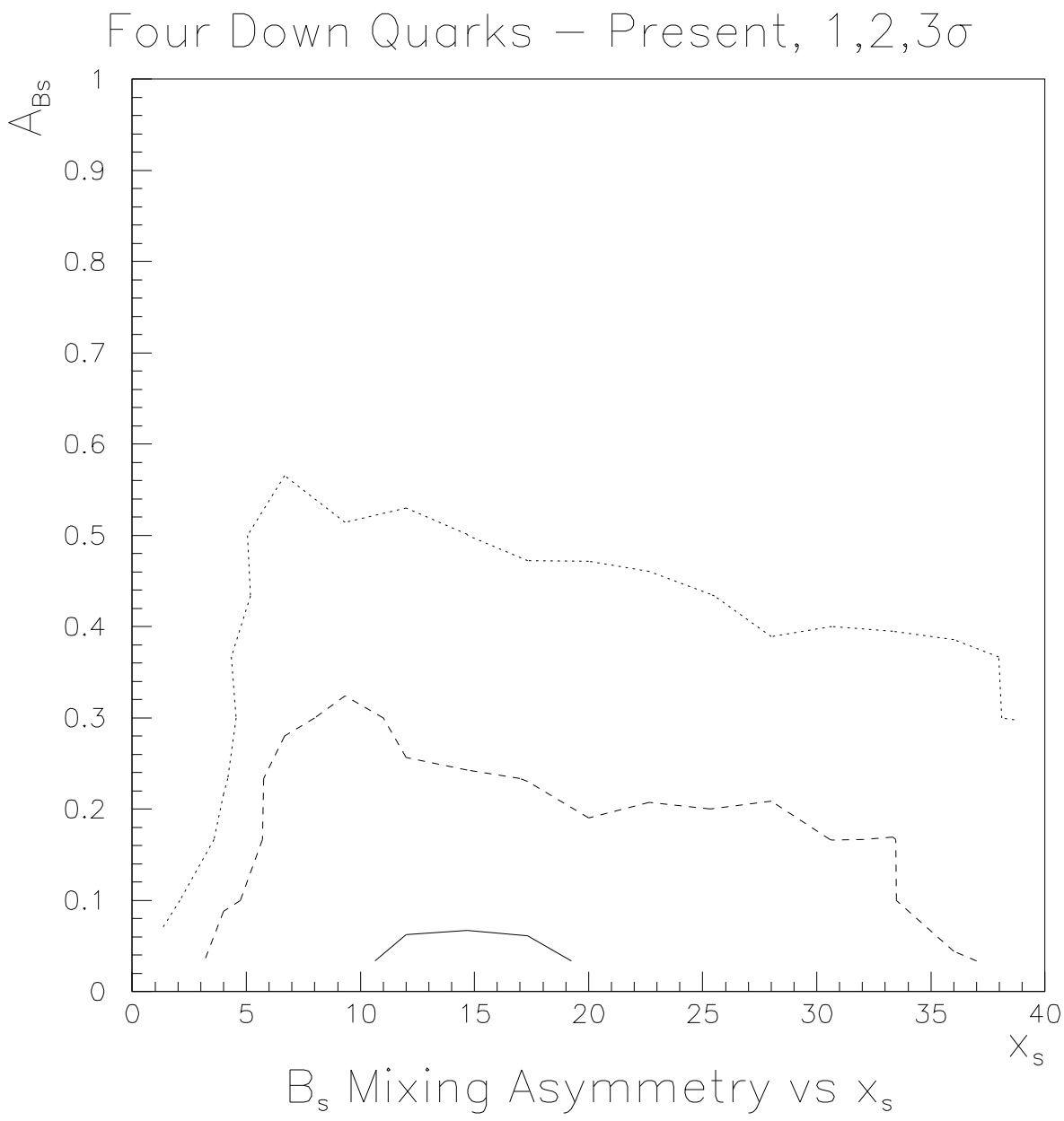

Four Down Quarks – Present, 1,2,3σ
A_{Bs}
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
X_s
B_s Mixing Asymmetry vs x_s

Fig. 6